IN THE SPECIFICATION

[0004] To ensure that a correct amount and quality of film is deposited or etched, substrate processing in a process chamber needs to be monitored during the processing. Plasma state of the process and chamber during processing needs to match that of a selected process in a "reference" chamber to ensure the chamber and process are functioning as expected and also correct endpoint detection can occur to terminate the process at the desired time. If the plasma state of the process and chamber during processing does not match that of a selected process in a "reference" chamber, a potential fault is detected and the operator is alarmed to take appropriate action. Details of how a chamber and process can be monitored during process to detect endpoint and fault have been disclosed in commonly assigned U.S. Pat. No. 6,368,975, entitled "Method and Apparatus For Monitoring A Process By Employing ~~Principle~~ Principal component Analysis", issued on Apr. 9, 2002 and its divisional application Ser. No. 10/341,696, filed on Jan. 14, 2003.

[0008] The invention relates to a method for comprehensive monitoring of semiconductor plasma processes. The invention monitors and compares plasma emission and RF characteristics of a process chamber under test to the plasma emission and RF characteristics of a reference process chamber using a multivariate technique, such as ~~principle~~ principal component analysis.

[0019] FIG. 7 is flow charts illustrating the steps involved in calibration processes according to an embodiment of the present invention that uses ~~principle~~ principal component analysis (PCA).

[0024] FIG. 12 is a flowchart illustrating steps of a method of matching the ~~principle~~ principal components of a faulty chamber with stored ~~principle~~ principal components data collected from chambers with known faults.

[0025] The invention involves measuring correlated attributes of a plasma process in a processing chamber, and by employing principal component

analysis to analyze the correlated attributes; process state and chamber state information may be easily and accurately obtained for the process. For convenience, the present invention is described herein primarily with reference to plasma etch processes and plasma-based correlated attributes (e.g., plasma electromagnetic emissions state and RF state). Details of how plasma emission spectrum data can be collected and how principal component analysis can be used to identify principal components have been disclosed in commonly assigned U.S. Pat. No. 6,455,437, entitled "Method and Apparatus For Monitoring The Process State of A Semiconductor Device Fabrication Process, issued on Sep. 24, 2002, U.S. pat. No. 6,413,867, entitled "Film Thickness Control Using Spectral Interferometry", issued on Jul. 2, 2002, and U.S. Pat. No. 6,368,975, entitled "Method and Apparatus For Monitoring A Process By Employing ~~Principle~~ Principal Component Analysis", issued on Apr. 9, 2002. All of the aforementioned patents are incorporated herein by reference in their entireties. RF power state data, such as RF voltage, current and phase can also be collected in a similar fashion and analyzed together with the OES data. The OES data and RF data are correlated with respect to time.

[0035] RF state data provide additional plasma state information that is complementary to the OES data. In one embodiment of the invention, OES data and RF data are collected during a polysilicon etching process before perturbation of a process being performed by a chamber and after the perturbed process has reached steady state. In one embodiment of the invention, the process parameters that are perturbed include: source power, bias power, chamber pressure, O_2 flow rate, HBr flow rate and Cl_2 flow rate. The perturbation amount is 10%. ~~Principle~~ Principal component analysis (PCA) is performed on the averaged OES signals and RF data before and after perturbation to find two most important steady (state) ~~principle~~ principal components (PCs), PC1 and PC2. The decomposition of the data matrix yields scores for the two ~~principle~~ principal components. The scores represent the coefficients of the ~~principle~~ principal components and indicate the divergence from the un-perturbed process.

Score "0" reflects the normal, un-perturbed process; therefore, the normal process has PC1 and PC2 scores of to be (0,0).

[0037] ~~Principle~~ Principal components are the eigenvectors of matrix $\mathbf{X}^T\mathbf{X}$. The columns of V are the eignvectors and the diagonal elements of Ω are the eigenvalues.

$$\mathbf{X}^T\mathbf{X} = \mathbf{V}\Omega\mathbf{V}^T \tag{2}$$

[0040] Figures 6A and 6B are plots of scores of ~~principle~~ principal components 1 and 2 as collected during etch chamber qualification. Fig. 6A is for OES analysis and Fig. 6B is for RF analysis. Fig. 6A shows that the perturbation of source power, chamber pressure and O_2 flow rate greatly affect the OES state; while Fig. 6B shows that source power, chamber pressure and bias power significantly affects the RF state. Perturbation of source power and perturbation of chamber pressure both greatly affect the OES and RF states. While perturbation of the O_2 flow rate affects the OES state more than the RF state and perturbation of the bias power affects the RF state more than the OES state. HBr and Cl_2 perturbation have weak effects on the OES and RF data. When the OES data and RF data are found not to correlate, such as O_2 flow rate and bias power perturbation in this example, or weak effects on OES and RF data by the perturbation, such as HBr and Cl_2 flow rate, signal enhancement of the data or selecting a narrower and more sensitive signal range of wavelength (for OES) and frequency (for RF) could be considered to ensure detection of process parameter variation.

[0043] At step 710, two periods ($\Delta t1$ and $\Delta t3$, see Fig. 8A and 8B) are identified within the collected data that correspond to the steady states of the process (before perturbation and after perturbation). One period ($\Delta t2$, see Figure 8A and 8B) of time is identified within the collected data that correspond to the transitional state of the process. A window of data for a number of different sample times (selected within the time periods, typically evenly sampled within

the period) can be examined. The number of sample times within the transitional period ($\Delta t2$) depends on the transitional state. If the transitional state is simple (Fig. 8A), the number of sample times is small. If the transitional state is more complex (Fig. 8B), the number of sample times is large to ensure sufficient samples of data track the transitional state. The collected data within the window is used to form a matrix having rows comprising the measured correlated attribute data and the columns comprising the time each attribute set was measured. The data within the matrix is mean centered so that singular value decomposition can be performed on the matrix and ~~principle~~ principal component eigenvectors are generated for the collected data within the matrix.

[0044] At step 712, principal component analysis (PCA) is performed on the collected data for the calibration process. At step 714, the ~~principle~~ principal components (PCs) for steady state and transitional state are identified for the process and the reference chamber. Additional perturbation processes can be conducted to collect more ~~principle~~ principal components until desired number of perturbation processes is reached. The method queries at step 716 whether the number of desired perturbations have been performed. If the query is negatively answered, the method proceeds to step 704. If the query is affirmatively answered, the method stops at step 726.

[0045] The calibration process illustrated can be improved by enhancing signals or by selecting a narrower and more sensitive signal range for the perturbation parameters that yielded weak effects on OES and RF data. It was shown earlier in Figure 6A and 6B that some perturbation parameters, such as O_2 flow rate, bias power, HBr flow rate, and Cl_2 flow rate, yielded weak effects on either OES data or RF data, or both OES and RF data. For these parameters, signal enhancement or selection of a narrower and more sensitive signal range can be included to ensure detection of changes in the parameter values. The need for signal enhancement or selection of a narrower and more sensitive signal range can be determined by decomposition of the OES and RF data

matrix (step 718) for the ~~principle~~ principal components. An example has been shown in Figure 6A and 6B. Perturbation parameters that yielded weak effects can be identified. The weak signals could be enhanced by amplifying post perturbation signals or a narrower and more sensitive wavelength range (narrower than 200-800nm) or frequency range could be reselected (step 720) to magnify the change. Once the degree of signal enhancement is determined during the chamber calibration run, the same degree of signal enhancement should be performed on the OES and RF data collected during chamber study run. PCA should be performed again (step 722) on the data that have been enhanced or reselected to identify steady and transitional ~~principle~~ principal components again. At step 724, final sets of ~~principle~~ principal components would be designated as reference steady (state) ~~principle~~ principal components (RSPC) and reference transitional (state) ~~principle~~ principal components (RTPC) for the "reference" chamber and perturbation parameters. The number of sets of RSPC and RTPC corresponds to the number of perturbation parameters.

[0046] FIG. 9 depicts a flow diagram of a method 900 of the operation of a chamber under study in accordance with the present invention. Once the reference ~~principle~~ principal components for the reference chamber and calibration process are generated by method 700, the method 900 performs process runs in the chamber that needs to be qualified or matched. The chamber could be a chamber in the chamber manufacturing area that needs to be qualified, a chamber that needs to be started up in a new fab or a chamber that has recently undergone some regular maintenance, such as wet clean. The "study runs" begin at step 902. Process and process sequences are run in the chamber under study at steps 904 and 906 that are identical to the processes run in the reference chamber at steps 704 and 706. At step 905, identical data collection procedures (same as step 705) are used and correlated attributes with the identical measurement times for similar processes are collected. The data collection terminates at step 908. At step 910, the OES and RF signals would be enhanced or signal range be reselected according to the algorithm developed at

step 720 of method 700. At step 912, PCA is performed on these collected correlated attributes and, at step 914; the method identifies steady (state) ~~principle~~ principal components SPC and transitional (state) ~~principle~~ principal components TPC for the chamber under study.

[0047] At step 916, the steady and transitional ~~principle~~ principal components (SPC and TPC) of the chamber under study are compared against correlated reference steady and transitional ~~principle~~ principal components (RSPC and RTPC) of the reference chamber by forming inner products of the correlating eigenvectors (or ~~principle~~ principal components). The resulting values of the inner products are between -1 and 1, with 1 giving a perfect process match, 0 gives no process match, while –1 give an opposite reaction to the process perturbation. The resulting values provide "matching" steady and transitional scores for the chamber under study.

[0050] Figure 10 is a diagram of a simplified case that has only one steady ~~principle~~ principal component and one transitional ~~principle~~ principal component for a process parameter perturbation. An ideal "matched" chamber should have steady score and transitional score both at 1. Statistic process control limits (SPC1, SPC2) can be established to determine whether the chamber under study pass the criteria. The statistic process control limits can be of other shapes. They define the boundaries of "matching" scores for the process chamber to be considered matched. For a complete chamber matching, typically more than one process parameter perturbation would be conducted. Multiple chamber matching control graphs similar to figure 6 would be needed and used.

[0052] Figure 11 depicts the process flow of a method 1100 for chamber fault diagnosis. At steps 1104 and 1106, process and process sequences are run in the chamber under study that are identical to the processes run in the reference chamber. At steps 1105 and 1108, identical data collection procedures are used and correlated attributes with the identical measurement times for similar processes are collected. At step 1110, the OES and RF signals would be

enhanced or signal range be reselected according to the algorithm developed at step 720 of method 700. At step 1112, PCA is performed on these collected correlated attributes. At step 1114, the method 1100 identifies steady (state) ~~principle~~ principal components SPC and transitional (state) ~~principle~~ principal components TPC for the chamber under study.

[0053] At step 1116, the steady and transitional ~~principle~~ principal components (SPC and TPC) of the chamber under study are compared against correlated reference steady and transitional ~~principle~~ principal components (RSPC and RTPC) of the reference chamber by forming inner products for the correlating eigenvectors (or ~~principle~~ principal components). Via query 1118, the method 1100 may perform further data collection using other perturbation of process parameters. The resulting values from the inner products provide "matching" scores for the chamber under study. Once the matching scores for all perturbation runs are collected, at step 1120, the matching scores are compared. The perturbation parameter(s) that yields the lowest matching scores can be identified. At step 1120, the possible source(s) of fault is related to the perturbation. For example, if the matching scores were low for the flow rate perturbation of one of the reactive gas, one would check the gas flow controller, calibrate the mass flow meter or check the fullness of the gas tank.

[0054] Past fault diagnosis runs with known faults could be very useful in fault diagnosis. The ~~principle~~ principal components of the current diagnosis runs can be compared with the ~~principle~~ principal components of past fault diagnosis that are stored in the memory. If there are good matches of the ~~principle~~ principal components, the source of fault can be identified, which would result in reducing the amount of work associated with pinpointing the source of fault.

[0055] Figure 12 shows the process flow of a method 1200 that identifies the source(s) of a fault 1200. The method 1200 begins at step 1202 and proceeds to step 1204 where the system retrieves the ~~principle~~ principal components that have the lowest matching scores with respect to the reference chamber. The

method 1200, at step 806, searches the library (or memory) for past diagnosis runs with known faults that have low matching score(s) for the same perturbed parameter(s). At step 1208, inner product computations of the correlated ~~principle~~ principal components are performed to obtain matching scores. A control limit can be established to determine if the ~~principle~~ principal components of the chamber under study sufficiently matches the ~~principle~~ principal components of the chamber with known fault. At step 1210, the method 1200 queries whether the matching scores pass a matching control limit. If the query is affirmatively answered, the method 1200, at step 1214, deems the fault retrieved from the memory to be a possible fault source for the chamber under study. If the query of step 1210 is negatively answered, the method proceeds to step 1212 where the method queries if additional diagnosis runs are available for comparison. If they are available, the method returns to step 1208 to process the next diagnosis run. If no other diagnosis runs are available, the method 1200 proceeds to step 1216. At step 1216, if no matching can be found with the known faults stored in the library, the case needs attention from experts. Once the source of fault is identified by the expert, the ~~principle~~ principal components, the matching scores, and the source of fault can be stored in the library for future diagnosis.